Satellite observations of long-term changes in tropical cloud and outgoing longwave radiation from 1985 to 1998

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[1] Cloud vertical distributions and radiation data from satellites taken between 1985 and 1998 were analyzed to determine the impact of clouds on outgoing longwave radiation (OLR) in the Tropics. Clouds with a 1-μm optical depth greater than 0.025 above 12 km decreased, while those below 12 km increased. The OLR mean and decadal trend were 254 Wm^{-2} and 3.9 Wm^{-2}/decade, respectively. The mean cloud and OLR results were used to derive a value of 0.36 for the tropical mean cloud longwave effective emissivity. Changes in cloud vertical distributions account for 40% of the OLR trend. A change in cloud effective emissivity of −0.026/decade could account for the remainder of the OLR changes. These changes suggest reduced mean cloud opacity, a drier troposphere, and a strengthened large-scale circulation in the Tropics during the period. *INDEX TERMS:* 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 1640 Global Change: Remote sensing; 3319 Meteorology and Atmospheric Dynamics: General circulation; 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology

1. Introduction

[2] Clouds play significant roles in the hydrological cycle and radiation budget of the Earth-atmosphere system. Decreases in cloud occurrence frequency, height, fractional amount, or emissivity can lead to increases in the outgoing longwave radiation (OLR), which cools the system. Conversely, increases in the same quantities can effect warming by reducing the OLR. Long-term observations of clouds and OLR can enhance the understanding and interpretation of cloud, radiation, and climate interactions. Furthermore, accurate knowledge of these types of cloud characteristics and their impact on the radiation budget is needed to reduce uncertainties in general circulation models and their predictions of climate changes [*IPCC*, 2001]. Relatively long records of cloud vertical distributions have been derived from measurements by the second Stratospheric Aerosol and Gas Experiment (SAGE II). Coincidentally, OLR was measured continuously during the same period by the Earth Radiation Budget Experiment (ERBE). Both SAGE II and ERBE were launched on-board the Earth Radiation Budget Satellite in October 1984. These two datasets are the only matched cloud and radiation budget records sufficient for studying decadal changes in cloud-radiation interaction. More recently, OLR has been measured by the Clouds and the Earth's Radiant Energy System (CERES) launched during November 1997 on the Tropical Rainfall Measuring Mission satellite. The present study uses these datasets to explore the consistency between long-trem changes in vertical cloud distributions, and OLR in the Tropics (20°S–20°N) between 1985 and 1998 and to improve current information on the cloud-radiation-climate interaction.

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2. Data and Analysis

[3] The SAGE II solar occultation measurements can be used to determine cloud occurrence frequency as a function of altitude for two groups of cloud—subvisual cloud (SVC) and opaque cloud (OC), at a 1-km vertical resolution [*Wang et al.*, 1996]. Opaque clouds are all of the clouds that have a vertical optical depth greater than about 0.025 at a 1.02-μm wavelength. They terminate the SAGE II profile and, therefore, prevent cloud detection below the OC altitude. The OCs generally correspond to all types of clouds except the SVC, which are typically thin cirrus clouds with optical depths less than 0.025 [*Sassen and Cho*, 1992; *Wang et al.*, 1996]. Several quantities describing the vertical distribution of OCs have been derived from the SAGE II measurements, but the uppermost opaque cloud (UOC) dominates the OLR [*Wang et al.*, 2001]. The frequency of the UOC corresponds to the lower limit of the OC frequency and is the quantity directly measured with SAGE II. Therefore, the vertical distribution of UOC is the quantity of interest here.

[4] The ERBE instrument consists of two packages—a cross-track scanner and a nonscanner [*Barkstrom*, 1984]. Each contains a complete, traceable system for in-flight calibration. Because the ERBE scanner stopped working after February 1990 and the nonscanner is still operating, the nonscanner provides the long-term record for this study. The scanner has three thermistor bolometers and the nonscanner package has four Earth-viewing active cavity radiometers. Both measure broadband reflected shortwave (0.2 to 5 μm), emitted longwave (5 to 50 μm), and total (0.2 to 50 μm) radiation at the top of the atmosphere. The instantaneous OLR is derived from the difference between the total and short wavelength measurements and corrected for anisotropy, then used to compute monthly averages over 2.5° and 10° regions for the scanner and nonscanner, respectively [*Wong et al.*, 2001]. Seasonal means are computed from the monthly averages. The CERES scanning broadband radiometer is based on precision thermistor bolometers and also includes a traceable in-flight calibration system [*Wielicki et al.*, 1996]. It measures broadband reflected shortwave, total, and window radiation at the top of the atmosphere. The CERES OLR is computed for 2.5° regions using the same approach as ERBE. Cloud longwave radiative forcing (CLRF) was derived only from the ERBE and CERES all-sky and clear-sky OLR scanner observations [*Ramanathan et al.*, 1989], because their relatively small footprints are required to separate clear and cloudy areas. The absolute accuracy of the seasonal mean OLR from ERBE is estimated to be roughly 1% and the long-term stability accuracy is about 0.5% (or 1 Wm^{-2}) over the data period [*Wielicki et al.*, 1999]. The CERES OLR measurements have absolute and stability accuracies of 0.5% and 0.2%, respectively [*Wielicki et al.*, 1999].

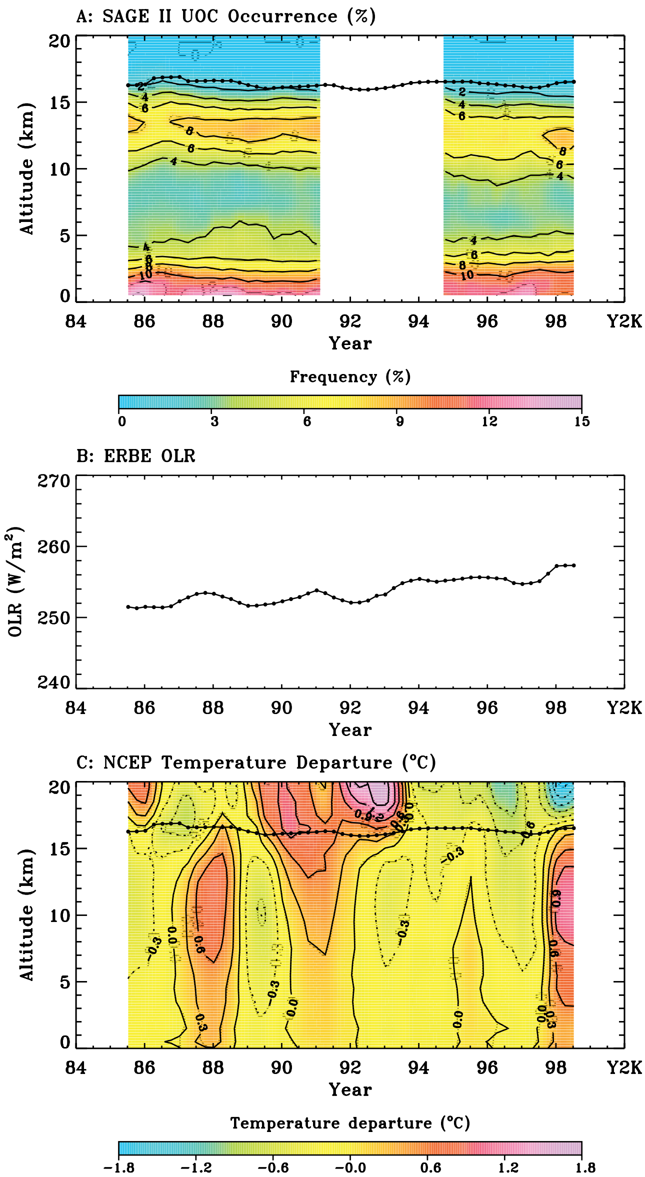

Figure 1. Interannual variation of the tropical (a) SAGE II UOC occurrence frequency, (b) ERBE NONSCANNER OLR, and (c) Tropospheric temperature departure from the mean, between 1985 and 1998. The dotted line in (a) and (c) indicates the tropopause.

[5] The interannual variations of the UOC on a seasonal basis (Figure 1a) show that more clouds occur in the boundary layer below about 3 km and in the upper troposphere above 10 km than in the other parts of the troposphere. This vertical variation of cloud frequency with a minimum in the middle troposphere is typical in the Tropics. The altitude of the center of the cloud layer in the upper troposphere appears to decrease between 1985 and 1998. The data gap between about 1991 and 1994 is a consequence of the heavy stratospheric aerosol loading from the June 1991 Pinatubo (15.1°N, 120.4°E) volcanic eruption that blocked profiling of the troposphere. The SAGE II cloud count is equivalent to a binomial experiment with the cloud frequency as the binomial parameter [*Wang et al.*, 2001]. The associated uncertainty of the derived frequency is estimated by using a statistical method [*Mendenhall and Schaeffer*, 1973].

[6] The corresponding ERBE interannual OLR (Figure 1b) increases by 6 Wm^{-2} over the same period with most of the changes occurring after the Pinatubo eruption. Approximately 2 Wm^{-2} of the increase can be attributed to the 1997–1998 El Niño event. Vertical profiles of interannual temperature anomalies were computed from the National Center for Environment Prediction (NCEP) reanalyses [*Kistler et al.*, 2001] by removing the 14-year means from the interannual temperature variations. The temperature departures (Figure 1c) reveal positive perturbations associated with the 1987, 1991 and 1997–98 El Nino events in the troposphere (below 16 km), and with the June 1991 Pinatubo volcanic eruption in the stratosphere (above 16 km).

[7] Linear regression was used to compute the decadal trends for the data in Figure 1. It is noted that the decadal trends are only representative of the 1985–1998 time period and should not be expected to extend before or after this time period. The relative maximum in mean UOC (8%) near 12.5 km (Figure 2a) is just below a strong decrease in UOC (−2%/decade) at 14.5 km and above the maximum increase in UOC (1.5% decade) at 10.5 km (Figure 2b). A relatively strong positive trend below 4 km peaks at about 1.2%/decade around 2.5 km. The mean ERBE nonscanner OLR increases at a rate of 4 Wm^{-2}/decade between 1985 and 1998. The average OLR for the period is 254 Wm^{-2} (see also *Wielicki et al.*, 2002). The associated standard deviations of these regression coefficients are 0.4 Wm^{-2}/decade and 0.1 Wm^{-2}, respectively. The reduction in UOC above 12.5 km (Figure 2b) is consistent with the increase in OLR because colder, higher clouds block longwave radiation emitted to space from the lower warmer troposphere and surface. The temperature trend analysis showed a small, significant decrease (−1° C/decade) just above the tropopause, and small positive temperature trends less than about 0.2 K/decade in the troposphere and at the surface consistent with earlier studies [*Hansen et al.*, 1997].

[8] The formula for CLRF [*Ramanathan*, 1977]

$$\mathrm{CLRF} = F = k \times \epsilon \times f \times \left(T_c - T_g\right) \qquad (1)$$

is used to infer cloud longwave effective emissivity ϵ from the satellite cloud and radiation budget observations. The cloud frequency, cloud temperature, surface temperature, and a constant are represented by f, T_c, T_g, and k, respectively. Note, the effective emissivity ϵ is a product of cloud fraction and emissivity. Because changes in cloud fraction and emissivity cannot be separately determined from SAGE II and ERBE data, the effective emissivity is used as a single quantity to study the impact of cloud on OLR. Because T_c is generally less than T_g, cloud presence leads to a negative value of CLRF, corresponding to a reduction in OLR by the clouds. Also, because the CLRF depends on the temperature difference between the cloud and the surface, high-altitude clouds, i.e. cirrus, assume the most important CLRF contribution due to their very low temperatures.

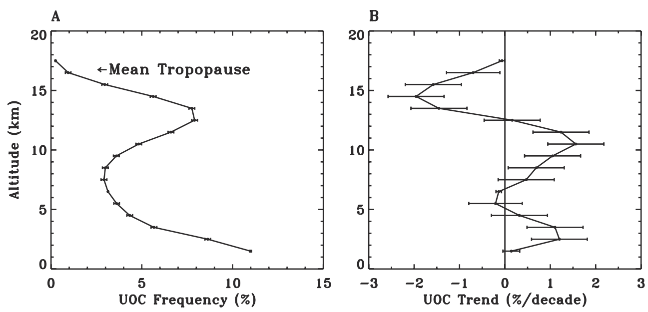

Figure 2. (a) Mean UOC occurrence frequency; and (b) UOC trend (1985–1998) in the Tropics. The horizontal bars indicate 95% confidence interval.

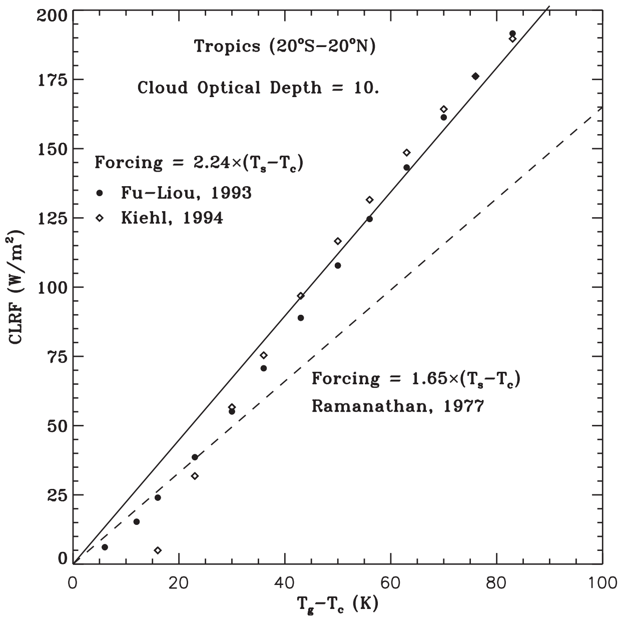

Figure 3. Tropical CLRF versus temperature difference between the surface and cloud. The dashed line indicates the CLRF model of *Ramanathan* [1977]. The dots (•) are the calculations using the radiative transfer model of *Fu and Liou* [1992, 1993]. The diamonds (◇) are the results using the analysis of *Kiehl* [1993]. The solid line is a linear fit to the data given by the dots and diamonds.

[9] Using perturbation theory and introducing $F = \overline{F} + F'$, $f = \overline{f} + f'$, and $\epsilon = \bar{\epsilon} + \epsilon'$ (the overbar represents the long-term mean and the prime denotes the time changing component), Equation (1) yields two expressions: the long-term mean,

$$\overline{F} = k \times \bar{\epsilon} \times \sum \left[\overline{f} \times \left(\overline{T_c} - \overline{T_g}\right)\right], \tag{2}$$

and the trend in CLRF,

$$F' = k \times \Big\{\epsilon' \times \sum \left[\overline{f} \times \left(\overline{T_c} - \overline{T_g}\right)\right] + \bar{\epsilon} \times \sum \left[f' \times \left(\overline{T_c} - \overline{T_g}\right)\right] + \bar{\epsilon} \times \sum \left[\overline{f} \times \left(T_c' - T_g'\right)\right]\Big\}. \tag{3}$$

Both of the above equations represent integrals over a vertical column to accommodate the fact that SAGE II provides cloud frequency with a 1-km vertical resolution, while the ERBE/CERES provides vertically intergrated OLR measurements. Also, because of the vertically intergrated satellite OLR data, it is only possible to determine vertical mean cloud effective emissivity in the present study. The results from *Wylie et al.* [1994] can be used to show that the effective emissivity is essentially a constant above 600 mb (~4 km). The coefficient k needed to compute ϵ is the rate of change in OLR with cloud-surface temperature difference. More recent cloud radiative transfer studies [*Fu and Liou*, 1992, 1993; *Kiehl*, 1993] yield greater values of k than previously used in studying OLR sensitivity to clouds (Figure 3). A linear fit to the more recent theoretical estimates of CLRF yields $k = 2.24$ Wm^{-2}/K (Figure 3), the value used here.

[10] The mean CLRF of −33 Wm^{-2} derived from the 60 months (January 1985 to December 1989) of ERBE scanner and the 8 months (January 1998 to August 1998) of CERES scanner measurements, and the mean cloud occurrence $\overline{f}$ (Figure 2a), along with the mean tropospheric temperatures and the mean surface temperature, were used in equation (2) to determine the mean cloud effective emissivity ($\bar{\epsilon}$). The calculation yields $\bar{\epsilon}$ = 0.36 with a standard deviation of 0.003.

[11] As indicated in equation (3), the trend in CLRF F' is a result of changes in cloud effective emissivity ϵ', the vertical distribution of cloud frequency f', surface temperature T_g', and cloud temperature T_c'. The SAGE II UOC trends (Figure 2b), the NCEP temperature profile, and the derived $\bar{\epsilon}$ were used to determine the part of the CLRF trend due to changes in cloud vertical distributions and $(T_c' - T_g')$, resulting in a value of 1.5 Wm^{-2}/decade and 0.02 Wm^{-2}/decade, respectively. Thus, if F' is known, ϵ' can be determined from equation (3). Because the background clear-sky OLR is essentially unchanged during 1985–1998, [*Wong et al.*, 2000] almost all of the decadal trend in the all-sky OLR must be due to changes in the cloudy portion of the Tropics. Therefore, the OLR trend of 3.9 Wm^{-2}/decade is assumed to be equivalent to F'. In fact, this ERBE nonscanner OLR trend (1985–1998) is very consistent with the independent estimate of the CLRF trend of 3.8 Wm^{-2}/decade using 60 months of ERBE scanner and 8 months of CERES scanner CLRF data. Employing the OLR trend in equation (3), the long-term change in ϵ' was determined to be −0.026/decade with a standard deviation of 0.008/decade. These results indicate that approximately 40% of the increased tropical OLR is a result of changes in cloud vertical distributions while the remaining 60% is due to changes in the cloud effective emissivity or optical thickness. The contribution due to changes in $(T_c' - T_g')$ is negligibly small. Using equation (1) and employing the calculated results of $\bar{\epsilon}$ and ϵ', along with the cloud frequency (Figure 1a) and temperature (Figure 1c) data, the CLRF mean and trend are determined to be −33 Wm^{-2} and 3.7 Wm^{-2}/decade, respectively, in good agreement with the ERBE/CERES observations, as expected (Figure 4).

3. Discussion and Concluding Remarks

[12] It should be recognized that the observed OLR increase of 3.9 Wm^{-2}/decade during 1985–1998 cannot be attributed to increases in greenhouse gas concentrations because the increased concentrations would trap more thermal radiation leading to reduced, not enhanced, OLR. Any decrease in water vapor above the cloud tops is not likely to account for much of the change, although this effect should be explored if reliable humidity data become available. An increase in OLR due to a decrease in cloud amount and/or optical depth should be mirrored by a decrease in the reflected shortwave radiation (RSR). *Wong et al.* [2001] reported that the RSR from the ERBE nonscanner exhibits a decreasing rate of −2.4 Wm^{-2}/decade between 1985 and 1999.

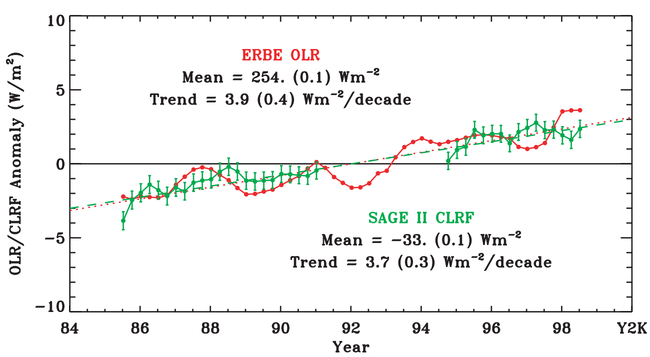

Figure 4. Tropical ERBE nonscanner OLR (red) and the SAGE II CLRF (green). In the SAGE II CLRF analysis, the cloud effective emissivity ($\epsilon(t) = \bar{\epsilon} + \epsilon' \times t$, where t is time) is employed. The vertical bar indicates the 95% confidence interval. The number in the bracket indicates the associated standard deviation.

The decrease in the albedo effect nearly cancels the OLR increase so that the net radiation turns out to be not statistically different from zero [*Wong et al.*, 2001]. In addition, the RSR record reveals that most of changes also take place after the Pinatubo eruption as in the OLR changes, pointing to the influence of changing cloud properties in the 1990s [*Wong et al.*, 2001]. These features further indicate that the observed all-sky OLR increase between 1985 and 1998 is most likely due entirely to changes in tropical cloud characteristics.

[13] The decrease in cloud frequency in the upper fifth of the tropical troposphere and the apparent change in cloud effective emissivity suggest that this layer of the atmosphere has become drier during 1985–1998. Although humidity fields are not available above 300 hPa in current versions of the NCEP analyses, other observations might provide support for this drying. The tropical large-scale Hadley and Walker circulations appear to have been strengthened in recent years due, to some extent, to greater warming at the surface than aloft [*Gaffen et al.*, 2000; *Chen et al.*, 2002]. Because subsidence associated with deep convection tends to dry the atmosphere and ascending motion tends to moisten the atmosphere, and because the area of subsidence is greater than that of rising motion, the strengthened tropical circulation could be the reason for the apparent reduced mean humidity and the downward shift of the cirrus cloud layer (Figure 1a) in the tropical troposphere. In this regard, the decreased high-altitude cloud and the increased OLR during 1985–1998 appear to be the signature of the decadal climate fluctuation in the Tropics, consistent with the long-term changes in the tropical vertical temperature distribution [*Gaffen et al.*, 2000].

[14] The present analysis indicates that approximately 40% of the increased tropical OLR is a result of changes in vertical distribution of cloud occurrence, while the remaining 60% can be attributable to changes in cloud emissivity and fractional amount that cannot be measured with SAGE II. A more comprehensive evaluation of the relationship between changes in cloud properties and the radiation budget will require more detailed vertical retrievals of cloud macro- and microphysical properties together with radiation budget data as currently being taken by CERES. Nevertheless, the general consistency between the unique, long-term SAGE II and ERBE results seen here is extremely important for building confidence in satellite remote sensing crucial to the detection and understanding of climate change [*Asrar et al.*, 2001] and ensures that these satellite datasets are valuable for validating cloud modeling in general circulation and climate prediction models.

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